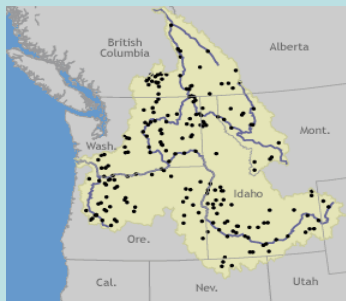


Columbia Basin Dams



Dams Under the Jurisdiction of the State of California



Parent – offspring smolting percentage

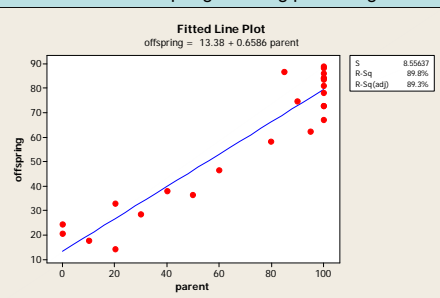


Figure 1. Parent-offspring regression for smolting for 10 family means for 200 families of F2 offspring (99-03 broods) of captive brood (96 brood year (F1)) derived from wild fish (P1) in 1996. Each data point represents the mean proportion of smolts produced by pooled lots of 10 families which were produced by 20 parents with specific histories of smolting (e.g. 60% for parents is equivalent to 12 parents that smolted and 8 that did not).

The Importance of Reservoirs in the Western U.S. for the Recovery of Endangered Populations of Anadromous Rainbow Trout (*Oncorhynchus mykiss*)

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ABSTRACT

Records from the late 1700's unpresent indicate that thousands of reservoirs for mining, irrigation, hydropower, ranching and domestic uses have been built on rivers and streams throughout California, Oregon, Washington and Idaho. The vast majority of these projects have not retained the ability for fish passage in one or both directions. As a consequence, hundreds of isolated populations of formerly anadromous fish, particularly steelhead (*Oncorhynchus mykiss*) were unintentionally created. Many of these populations undoubtedly died out or were altered with additions of hatchery fish, however, it is likely that when conditions were favorable many populations adapted to their new environments and remain to this day. Because of severe population declines of anadromous fish in recent decades, these isolated populations may, in some cases, retain the majority of the genetic heritage of many distinct population segments of both anadromous and resident forms of *O. mykiss*. To determine if captive populations of F_1 offspring of fish thus isolated for decades can still produce smolts that adapt to seawater and successfully return to spawn as ocean-ranched adults, we produced 10 families each of F_1 offspring of pure lines of anadromous steelhead and resident rainbow trout, (descendants of a previous stocking 70 years before from the same anadromous steelhead stock) plus reciprocal hybrid lines. We repeated this design for five broods (200 families in total) from the same captive year class (1996). Smolt production varied substantially between lines and between brood years with the anadromous line producing significantly more smolts than the resident line in four of the five years. Smolt production was related more to smolting history of the parents than genetic origin (line). Marine survival data, available for 3 complete broods and part of a fourth, indicated however, that survival of smolts, was related more to genetic origin than to smolting history of the parents. Smolting rates and marine survival of the F_2 progeny were similar to, or higher, than those of the F_1 progeny, indicating that completely captive broodstock, derived from isolated populations, could be an important component of a recovery plan for endangered stocks of anadromous rainbow trout.

OVERVIEW

Massive habitat degradation from dam construction, farming, logging and urbanization has resulted in dramatic reductions in populations of trout and salmon throughout the Western U.S. in the last century. These reductions have been severe enough to require the listing of the majority of the distinct population segments (DPS) of steelhead, the anadromous form of *Oncorhynchus mykiss*, as endangered under the Endangered Species Act (ESA). As part of the listing process, recovery plans, which identify a path to recovery of each listed DPS, are required to be developed. In some cases, recovery plans include augmentation of the extant population with fry, juveniles or adults that have been produced through the artificial propagation of gametes collected from the remaining wild fish. In many cases the remaining population is so small that any removal of gametes represents a risk to its continued survival, and, numerically, represents a severe danger of inbreeding and its associated depressive effects, to the population. Ironically, the very dams and associated reservoirs that imperil anadromous populations today, may still retain the bulk of the ancestral genetic legacy which now may reside in the resident populations of *O. mykiss* trapped behind the dams for many decades (Deiner et al. 2007). Recent research (Pella and Masuda 2004) has demonstrated that, in some cases, these resident forms retain the ability to produce the anadromous forms and these can survive a wild marine migration and successfully return to spawn. Gametes of wild resident forms can also be brought into a hatchery environment to produce pure lines of resident forms, or, mixed with gametes of related anadromous forms, and produce anadromous smolts that successfully survive a wild marine migration (Thorwer and Joyce 2004). While this form of supplementation is used, it is expensive and difficult to annually trap fish in the wild and also presents a continued handling risk to already depleted populations.

If offspring could be produced after a single generation of complete captivity that still retained critical fitness elements (e.g. smolt production, smolt size, marine survival, adult size, etc.), the increase in production of gametes would be substantial, and, as long as the appropriate genetic concerns are addressed, could improve the potential success for restoration with potentially lower cost and risk. In our experiment, we collected gametes from a wild, anadromous population of steelhead and from a wild resident population that had originated from the anadromous population 70 years earlier. We made pure lines and reciprocal hybrid lines from the gametes and, after normal hatchery rearing, released about half of the resulting smolts to the ocean and retained the other half in captivity for culture to adult. From the captive adults, we produced offspring in five sequential years, recreating all the lines and compared the resulting smolts + adults to the siblings of their parents that had been released earlier.

Shown right: Sexually mature, five year old male steelhead; one of several thousand captive broodstock fish used to produce the five broods of offspring compared in this experiment to determine the utility of this technology for recovering endangered, anadromous *O. mykiss* populations. Captive adults such as this one were raised in freshwater only, or a combination of freshwater and marine net-pens. Their offspring and those produced from gametes from wild parents, were used to compare survival and growth in captivity, and, at liberty after release, to determine the broods of offspring of captive broodstock fish of pure anadromous or pure resident origin had similar smolting, growth and survival characteristics as those produced from gametes collected from wild parents.



CONCLUSIONS

The results of this study demonstrate that captive broodstocks of populations of resident *O. mykiss* from lakes and reservoirs where anadromous populations were formerly present, are capable of producing offspring and adults with similar fitness characteristics (of those measured in this study) as those of offspring of wild fish reared under similar conditions. Of particular importance is the very similar performance of offspring, whether the parents were reared entirely in freshwater, or, when using a combination of freshwater and seawater. Reduced dependence on the marine phase of rearing greatly reduces costs associated with expensive pumped seawater systems or marine net-pen sites. In some cases, particularly colder areas, poorer freshwater growing conditions that reduce the average fish size also allow for maintenance of larger broodstock populations, for a given cost, which can reduce the potentially catastrophic impacts of inbreeding depression (Thrower and Hard, in press). Araki et al (2006) demonstrate the successful integration of supplemented fish of appropriate genetic background and wild fish into a supplementation program. Denier et al (2007) document the existence of genetically similar anadromous and reservoir-sequestered resident fish of formerly anadromous origin in a California reservoir. Thrower and Joyce (2004) demonstrate that resident fish, sequestered for decades in freshwater but of anadromous origin, are capable of surviving in a wild marine environment and that this study demonstrates that captive broodstocks of anadromous fish derived from wild fish can produce viable smolts and adults whether captive fish are retained in freshwater or developed in a freshwater-seawater program. These studies indicate the wide range of opportunities available for recovery planning for endangered population segments of *O. mykiss*, and, the critical role for native populations sequestered in reservoirs throughout the western U. S.

Table 1. Early maturation, smolting rates, smolt size, and marine survival for five broods of offspring produced from a single generation of captive fish produced from collections of gametes from wild fish in 1996. Sibling fish of the 1996 brood captive fish were released to evaluate marine survival (Thrower et al. 2004) and those results are included for comparison.

[illegible]

* Marine survival adjusted for incomplete returns (2-Ocean recovers only to day

Smolt Size

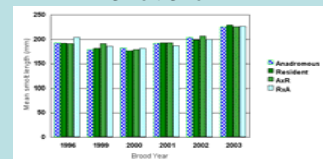


Figure 2. Mean length of smolts from F_1 progeny of wild fish (1996) and F_2 progeny of ca

Table 2. Mean snout-fork length (mm) and mean weight (g) for mature adult male whitefish age 4 (juvenes age 2) and 5 (juvenes age 3) from tagged releases of juveniles derived from gametes from wild or captive parents for four lines: AXA - pure anadromous (Saginaw Creek); RXR - pure resident (Saginaw Lake); RXR - Anadromous female X Resident male; RXA - Resident female X

[illegible]

Grey box indicates no significant difference between lines within brood
Pink box indicates significant difference ($p < 0.05$) from other lines within brood

Table 2. Mean snout-fork length (mm), mean weight (g), total egg weight (g), mean egg weight (g) and total egg number for mature, age 4 (two years at sea), female steelhead recovered at the Sashin Creek weir from tagged residents of juveniles derived from wild or captive parents for four lines: ARA – pure anadromous (Sashin Creek), RRR (non-resident) (Sashin Creek), AWR – first-generation female X resident male, RYA – resident female X non-resident male.

[illegible]

Grey box indicates no significant difference between lines within brood

Table 4. Mean snout-to-fork length (mm), mean weight (g), total egg weight (g), mean egg weight (g) and total egg number for mature, age 5 (three years at sea), female steelhead recovered at the Jackson Creek weir from tagged releases of juveniles derived from gametes from wild or captive parents for four lines: ADA – pure anadromous (Jackson Creek); ADA

Year	Country	City	Type of housing	Climate				Energy				Water				Waste			
				Temp (°C)	Humidity (%)	Wind (km/h)	Sun (h)	Electricity (kWh)	Gas (m³)	Water (liters)	Waste (kg)	Recycling (%)	Composting (%)	Landfill (%)	Incineration (%)				
2018	USA	Los Angeles	Single-family detached	75.0	67.0	15.0	250.0	12,000	1,500	150	10.0	5.0	85.0	10.0	5.0	80.0	5.0		
2019	USA	Los Angeles	Single-family detached	76.0	68.0	16.0	260.0	12,500	1,550	155	10.5	5.5	85.5	10.5	5.5	80.5	5.5		
2020	USA	Los Angeles	Single-family detached	77.0	69.0	17.0	270.0	13,000	1,600	160	11.0	6.0	86.0	11.0	6.0	81.0	6.0		
2021	USA	Los Angeles	Single-family detached	78.0	70.0	18.0	280.0	13,500	1,650	165	11.5	6.5	86.5	11.5	6.5	81.5	6.5		
2022	USA	Los Angeles	Single-family detached	79.0	71.0	19.0	290.0	14,000	1,700	170	12.0	7.0	87.0	12.0	7.0	82.0	7.0		
2018	Germany	Berlin	Apartment	10.0	75.0	12.0	150.0	8,000	1,000	100	5.0	2.0	70.0	5.0	2.0	70.0	2.0		
2019	Germany	Berlin	Apartment	10.5	76.0	13.0	160.0	8,200	1,020	102	5.5	2.5	71.0	5.5	2.5	71.0	2.5		
2020	Germany	Berlin	Apartment	11.0	77.0	14.0	170.0	8,400	1,040	104	6.0	3.0	72.0	6.0	3.0	72.0	3.0		
2021	Germany	Berlin	Apartment	11.5	78.0	15.0	180.0	8,600	1,060	106	6.5	3.5	73.0	6.5	3.5	73.0	3.5		
2022	Germany	Berlin	Apartment	12.0	79.0	16.0	190.0	8,800	1,080	108	7.0	4.0	74.0	7.0	4.0	74.0	4.0		
2018	Japan	Tokyo	Apartment	15.0	80.0	10.0	200.0	10,000	1,200	120	8.0	3.0	75.0	8.0	3.0	75.0	3.0		
2019	Japan	Tokyo	Apartment	15.5	81.0	11.0	210.0	10,200	1,220	122	8.5	3.5	76.0	8.5	3.5	76.0	3.5		
2020	Japan	Tokyo	Apartment	16.0	82.0	12.0	220.0	10,400	1,240	124	9.0	4.0	77.0	9.0	4.0	77.0	4.0		
2021	Japan	Tokyo	Apartment	16.5	83.0	13.0	230.0	10,600	1,260	126	9.5	4.5	78.0	9.5	4.5	78.0	4.5		
2022	Japan	Tokyo	Apartment	17.0	84.0	14.0	240.0	10,800	1,280	128	10.0	5.0	79.0	10.0	5.0	79.0	5.0		
2018	UK	London	Apartment	12.0	70.0	11.0	180.0	9,000	1,100	110	7.0	2.5	72.0	7.0	2.5	72.0	2.5		
2019	UK	London	Apartment	12.5	71.0	12.0	190.0	9,200	1,120	112	7.5	3.0	73.0	7.5	3.0	73.0	3.0		
2020	UK	London	Apartment	13.0	72.0	13.0	200.0	9,400	1,140	114	8.0	3.5	74.0	8.0	3.5	74.0	3.5		
2021	UK	London	Apartment	13.5	73.0	14.0	210.0	9,600	1,160	116	8.5	4.0	75.0	8.5	4.0	75.0	4.0		
2022	UK	London	Apartment	14.0	74.0	15.0	220.0	9,800	1,180	118	9.0	4.5	76.0	9.0	4.5	76.0	4.5		
2018	Canada	Toronto	Single-family detached	45.0	60.0	14.0	200.0	11,000	1,400	140	12.0	4.0	88.0	12.0	4.0	88.0	4.0		
2019	Canada	Toronto	Single-family detached	46.0	61.0	15.0	210.0	11,200	1,420	142	12.5	4.5	88.5	12.5	4.5	88.5	4.5		
2020	Canada	Toronto	Single-family detached	47.0	62.0	16.0	220.0	11,400	1,440	144	13.0	5.0	89.0	13.0	5.0	89.0	5.0		
2021	Canada	Toronto	Single-family detached	48.0	63.0	17.0	230.0	11,600	1,460	146	13.5	5.5	89.5	13.5	5.5	89.5	5.5		
2022	Canada	Toronto	Single-family detached	49.0	64.0	18.0	240.0	11,800	1,480	148	14.0	6.0	90.0	14.0	6.0	90.0	6.0		

Gray box indicates no significant difference between lines within brood
Pink box indicates significant difference ($p \leq 0.05$) from other lines within brood

Marine Survival

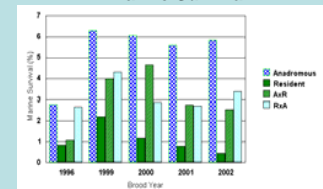


Figure 4. Marine survival of F_1 (1996) brood smolts produced from wild parents, and F_2 (1999–2002) brood smolts produced from captive parents of pure anadromous, pure resident, and reciprocal hybrid lineages showing consistently higher survival of the pure anadromous lineage over the pure resident lineage and the intermediate survival of the hybrids. Survival of the 2002 brood is based on estimates of returns of two-ocean fish only.